Computational fluid dynamics analysis of flat-plate and v-grooved solar heat collector of different materials for plastic waste drying

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ABSTRACT Plastic waste pollution has become one of the most critical environmental issues in the recent years as it adversely affects the ecosystem in many ways. River has been reported for playing an important role in transporting plastic waste into the environment and continued efforts have been done to prevent, control, and treating plastic waste intending to support river conservation. In this present work, computational fluid dynamics (CFD) analysis was conducted to study the performance of solar heat collector (SHC) as a baseline study for the application of plastic drying at the post-treatment stage for recycling and upcycling of plastic waste. SHCs incorporated with different absorber configuration (flat and V-grooved) and absorber material (aluminum and copper) were tested in the aspect of heat transfer and fluid flow characteristics to identify the enhancement mechanism occurs in the collector. The findings indicate that SHC with V-grooved copper absorber exhibits highest collector efficiency (44.95%). However, the application of aluminum absorber would be sufficient for the case where low velocity drying process is performed.

KEYWORDS: Plastic waste; Drying; Solar Dryer; Computational Fluid Dynamics; Simulation
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INTRODUCTION

Plastic pollution remains one of the most critical environmental issues and has contributed to major environmental problems of many forms such as water pollution, air pollution, and land pollution (Mrowiec, 2017; United Nations Environment Programme (UNEP), 2021; Verma et al., 2016). Despite having plenty of arguable findings reported that plastic pollution has a bigger effect on either the ecosystem in water, air or land, continued efforts to tackle plastic pollution in general include preventing waste from entering the environment, controlling the spread of pollution, and incorporating post-treatment on plastic waste as a step towards sustainable development. According to recent research, river has been identified as one the major channel for the transport of plastic waste to the environment (Karlsruher Institut für Technologie (KIT), 2022). Upon collection of plastic waste from the river, a recycling or upcycling production chain that begins with cleaning and drying of the plastics collected are performed. This process is essential as the condition of feedstocks (plastic waste) defines the quality of end-products produced. However, drying is an energy extensive process and employing open sun drying would results unsatisfactory drying performance for plastic drying. Therefore, solar drying is considered a promising alternative for this application.

Two solar heat collectors with different air flow configuration were proposed and tested previously on UMS Eco-Solar Dryer, namely: single-pass and multi-pass. In an attempt to improve the thermal performance of SHC, modification on the existing drying system is essential. As reported in the literature, heat transfer in the solar heat collector can be achieved through several approaches such as increasing the convective surface area of absorber plate, create turbulence flow in the air passage, extend the retention time of drying air in the collector, and increase thermal conductivity of absorber plate. Based on literature, the application of V-grooved copper absorber plate fulfilled the enhancement features mentioned. Desisa and Shekata (2020) reported that V-grooved absorber plate

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exhibits better performance that flat-plate in term of thermal efficiency, outlet temperature, air velocity, and pressure drop due to the turbulence airflow created by the sharp edges of corrugation. In addition, maximal heat transfer is expected to occur between the absorber and air fluid by incorporating V-grooved design due to the increment in surface width (Abuşka & Şevik, 2017). In term of material of construction, copper is preferable over aluminium due to its high thermal conductivity. However, considering relatively higher cost is required, it is vital to study the viability of using copper absorber plate for drying, considering both economical and performance aspect.

METHODOLOGY

In this study, Computational Fluid Dynamics (CFD) analysis was performed to investigate the thermal characteristics of solar heat collectors (SHCs) incorporated with enhancement features on the absorber plate in the aspect of the material of construction and geometrical design used. Improvements proposed in this study were made by taking a proven drying technology developed by Universiti Malaysia Sabah, namely UMS Eco-Solar Dryer as a baseline study (Lim et al., 2021; Tan et al., 2022). The initial design of SHC with black-painted aluminum cans as an absorber has initiated the necessity of air passage modification to further enhance heat transfer between the absorber plate and air medium. In this study, four SHCs with different configuration were tested – SHC with aluminum flat-plate (SHC AL-FL), SHC with copper flat-plate (SHC CU-FL), SHC with V-grooved aluminum plate (SHC AL-VG), and SHC with V-grooved copper plate (SHC CU-VG). Parameters observed are the temperature distribution, collector efficiency, velocity vector, and pressure drop, which obtained solely through CFD simulation.

Geometry and Meshing of Computational Model

The geometrical model of SHC used for the computational analysis is as illustrated in Figure 1 for flat-plate and V-grooved absorber plate, respectively, with a dimension of 2112 mm length, 920 mm width, and 100 mm height. The curvature angle for V-grooved absorber plate is 60º with triangle height of 20 mm to ensure optimum air gap (25 mm) between the transparent cover and absorber plate for greenhouse heating. Due to the geometry limit of ANSYS Fluent (student version), V-grooved pattern covers only a length of 670 mm to ensure the model does not exceed 300 faces. This condition is sufficient to study the heat transfer and fluid characteristics across the collector.

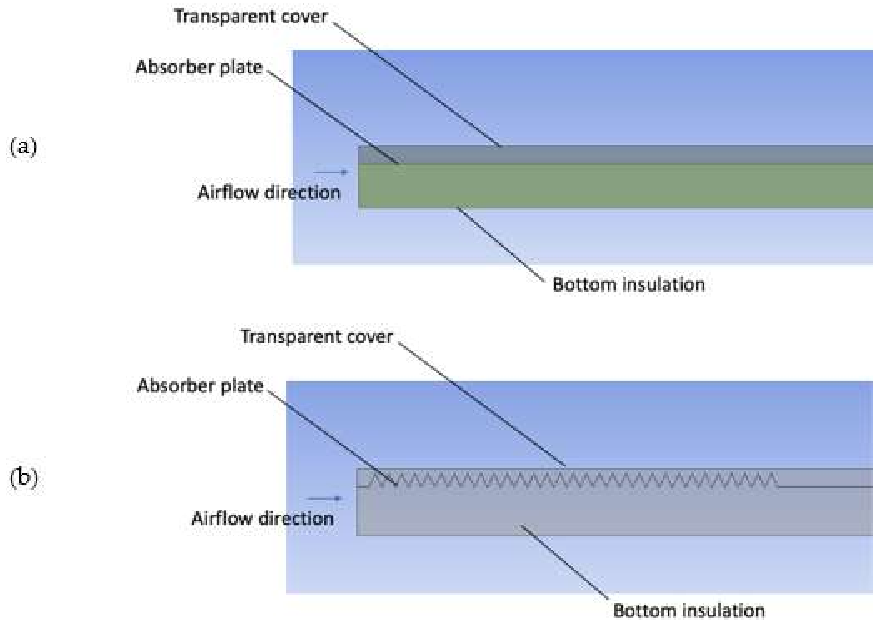

Figure 1. Cross-sectional front view of solar heat collector with (a) Flat-plate and (b) V-grooved plate.

Two fluid domains are identified in the model: 1. flow passage between the transparent cover and absorber plate, 2. flow passage between the absorber plate and insulator. The component domain includes transparent cover (top wall), SHC frame wall (bottom and side wall), absorber plate, air inlet, and air outlet. Meshing of model is generated with element size of 0.0075 to create fine mesh sufficient to visualize air flow pattern at the curvature edges of V-corrugation.

Boundary Condition

Default energy model was used to solve energy equation involved in the domain and realizable k-epsilon with enhanced wall treatment was adopted for the entire numerical simulation. In this study, solar load model (SLM) with solar ray tracing algorithm was used to account for solar radiation. Top wall (transparent cover) of the domain was identified as semi-transparent solar tracking model with 0.9 transmissivity. Bottom and side wall (SHC frame) were considered as adiabatic (zero heat flux) and no-slip boundary condition. All interfaces were assigned as coupled wall. The inlet was identified with mass flow rate of 0.012 kg/s and 0.005 kg/s for the bottom and upper fluid domain, respectively for the case where the ambient air velocity is 0.6 m/s. The outlet section was identified as pressure outlet. Thermal characteristics of materials involved are listed in Table 1.

Table 1. Thermal characteristics of materials for boundary conditions input.

Component	Material	Size	Material Properties		
			Thermal conductivity (W/m-K)	Density (kg/m³)	Specific heat (J/kg-K)
Cover	Acrylic	2.11×0.91×0.005m	0.19	1190	1470
Absorber	Copper	2.11×0.91×0.002m	401	8960	390
Absorber	Aluminium	2.11×0.91×0.002m	237	2700	900
Baffles	Aluminium	0.003m thickness	233.49	2719	903
Frame	Aluminium	0.008m thickness	233.49	2719	903
Insulator	Rockwool	0.025m thickness	0.039	60	1030

Validation

No experimental investigation is performed in this study for validation purpose as this work solely serve as a preliminary study prior for the fabrication of an improved solar heat collector prototype. However, the relevancy of CFD model developed has been proven in previous work that study the thermal performance of UMS Eco-Solar Dryer through experimental and CFD analysis (Lim et al., 2021; Tan et al., 2022). The trend of temperature distribution simulated shows good agreement to the experimental result with percentage error ranged from 3.13 % to 5.73 %.

RESULT AND DISCUSSION

Effect of Absorber Material on The Performance of SHC

Temperature variation at the outlet of SHC with different configuration is shown in **Table 2** along with the corresponding collector efficiency calculated. It can be observed in both flat-plate and V-grooved SHC that the application of copper as absorber indicates a slight improvement in collector efficiency of less than 1% increment from aluminum absorber plate. This finding is in accordance with Shariah et al. (1999) that studied the effect of absorber thermal conductivity on the performance of solar water heater. As reported, the characteristics factor only increases by 3% when aluminum is replaced by copper. The possible explanation on this matter would be air is considered a weak heat transfer medium compared to water hence, resulting less significant effect on heat transfer enhancement by replacing a higher thermal conductivity material as absorber.

Besides, for the application of low velocity drying, poor heat transfer between the fluid and the heated absorber surface will results the generation of 'hot spot' region across the plate. Consequently, this will increase the potential of heat loss from the collector to the external surrounding. The significance of 'hot spot' on solar heat collector was also reported by (Hu et al., 2019). Hence, in the case of drying where low velocity is required, using higher thermal conductivity material (copper) indicates equally higher heat loss from the system. For the case of plastic drying where high air velocity is required, the presence of 'hot spot' can be eliminated.

Table 2. Temperature variation at the outlet of solar heat collector under constant velocity = 0.2 m/s.

Solar heat collector configuration	Average outlet temperature/ ºC	Temperature difference/ ºC	Collector efficiency/ %
SHC AL-FL	53.4785	26.4785	37.42
SHC CU-FL	53.6575	26.6575	37.67
SHC AL-VG	58.8030	31.8030	44.95
SHC CU-VG	58.8045	31.8045	44.95

Effect of absorber geometrical design on the performance of SHC

Two geometry absorber plate have been considered in this study – flat-plate and V-grooved. The latter geometry ensure heat transfer enhancement is achieved in the aspect of collector efficiency by increasing the total convective surface area on the absorber. Other performance parameters observed in this section include the air flow pattern created across the absorber plate and the pressure drop obtained in the air passage. As presented in **Table 2**, incorporating V-grooved absorber plate improved the collector efficiency by 7.53% and 7.28% for aluminum and copper, respectively. This can be explained by observing the temperature profile established in the air passage.

Temperature distribution illustrated in **Figure 2** and **Figure 3** shows that a more uniform heat distribution can be achieved in CU-VG SHC. High temperature zone found in **Figure 2** imply that heat trapped in the upper air passage was not transferred to the bottom air passage effectively. This finding is in contrast with the SHC design shown in **Figure 3**. Smaller temperature gradient observed in this design indicates that thermal equilibrium of fluid is achieved between the upper air passage and lower air passage.

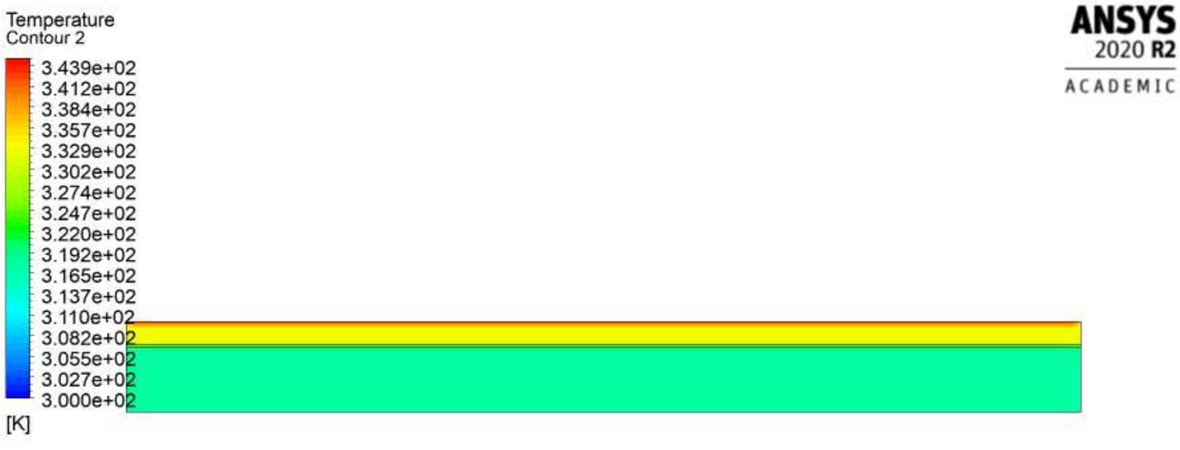

Figure 2. Temperature distribution at cross-sectional front view (normal to airflow direction) in CU-FL SHC.

Figure 3. Temperature distribution at cross-sectional front view (normal to airflow direction) in CU-VG SHC.

Large temperature gradient is observed in CU-FL SHC imply that heat absorbed on the absorber plate is not fully utilized hence, resulting lower collector efficiency. This can be inferred as turbulence airflow created in V-grooved SHC increases the heat transfer rate between the absorber and fluid. It can be noticed from **Figure 4** and **Figure 5** that airflow in CU-VG SHC is more intense due to the sharp edge of corrugation. The simulated air velocity in CU-FL SHC and CU-VG SHC is found to be 0.22 m/s and 0.26 m/s, respectively.

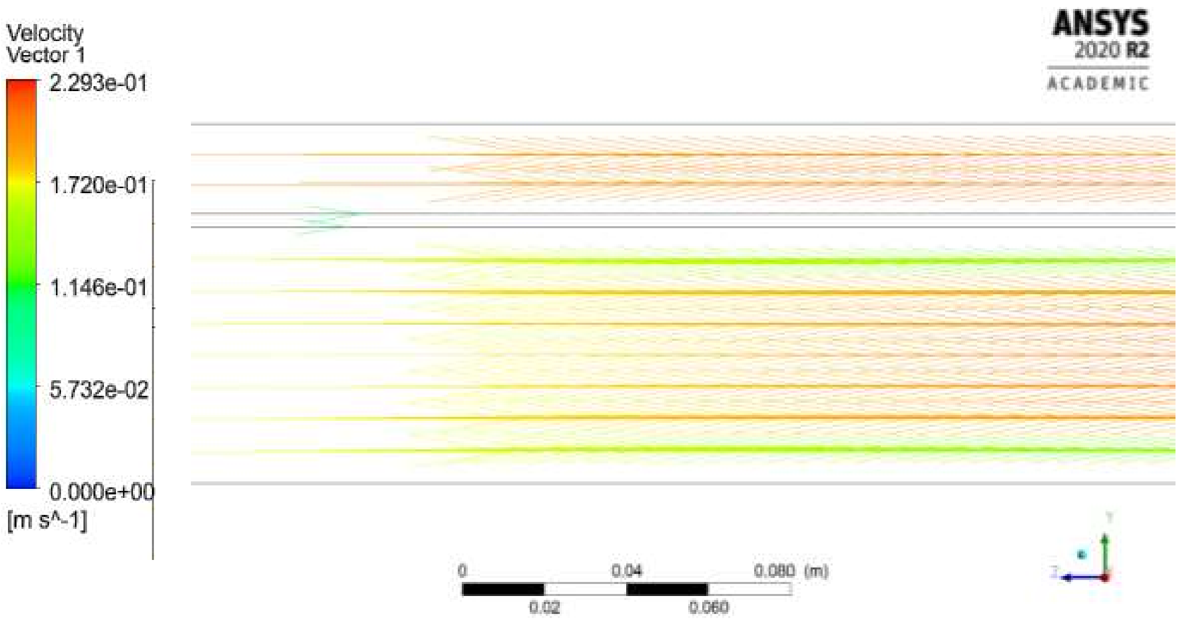

Figure 4. Velocity contour at cross-sectional side view (parallel to airflow direction) in CU-FL SHC.

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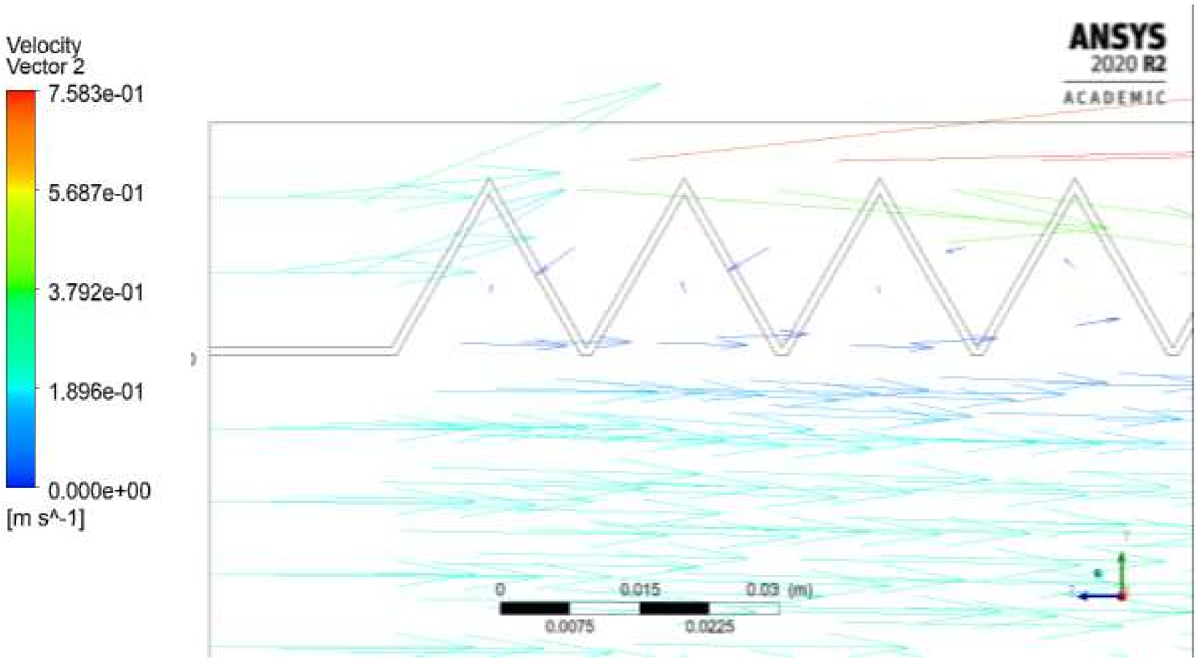

Figure 5. Velocity contour at cross-sectional side view (parallel to airflow direction) in CU-VG SHC.

In both flat and V-grooved absorber plate, significant pressure drop was observed in the air passage between the transparent cover and absorber plate. However, more pressure drop is observed in CU-VG SHC with value of 4.602 Pa than that of CU-FL SHC with 0.151 Pa. This finding is in accordance with Singh and Singh (2018). It can be explained that both reduced space in the air passage and the presence of turbulator provokes pressure drop across the collector (Romdhane, 2007). However, considering the collector efficiency computed in section **Error! Reference source not found.**, it can be concluded that the pressure drops produced does not overweigh the enhancement effect in the SHC.

CONCLUSION

Thermal characteristics of solar heat collector with different absorber material and geometrical design were studied through CFD analysis. Heat transfer and fluid flow parameters observed in this study include solar heat collector outlet temperature, collector efficiency, air velocity, and pressure drop. The findings obtained are listed as follow:

1. Replacing aluminum with copper absorber plate improves the performance of solar heat collector in term of collector efficiency. However, this improvement was considered not significant as the increment of efficiency is less than 1%.
2. Collector efficiency increases by 7.53% and 7.28% for V-grooved aluminum and copper plate, respectively from flat-plate absorber.
3. Under constant mass flow rate, the air velocity observed in the air passage is 0.22 m/s and 0.26 m/s for flat-plate and V-grooved absorber plate, respectively.
4. Despite the fact that V-grooved SHC provokes higher pressure drop in the collector, high collector efficiency obtained in both AL-VG and CU VG indicates that the pressure drop produced does not overweigh the enhancement effect in the SHC.

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